FIBER OPTICS

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Topics Covered :-

→ Parts of optical fiber
→ Transmission of signal, TIR
→ Critical Angle
→ Acceptance angle and acceptance cone
→ Numerical Aperture, V-number
→ Types of fiber
→ Dispersion and Attenuation

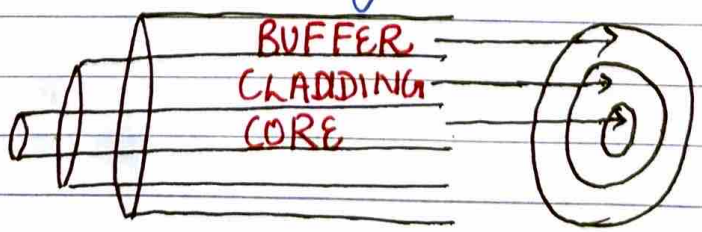
Optical fiber is a thin, flexible transparent fiber made of glass or plastic that transmits light signals from one place to another by total internal reflection.

Parts of optical fiber

1) Core : Central region of fiber through which light propagates.

2) Cladding : Surrounds the core and has lower refractive index to enable total internal reflection.

3) Buffer : Protective plastic layer that prevents mechanical damage.



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FIBER MANUFACTURE

1. Glass - Glass Fiber

→ Making core as well as cladding of glass.
→ Glass as silica (SiO_2) with refractive index of 1.458
→ For transmission of signal, refractive index of core (n_1) should be greater than cladding refractive index (n_2), i.e, $n_1 > n_2$.
→ Germanium oxide (GeO_2) and Phosphorous Oxide (P_2O_5) is added to increase refractive index for making core of optical fiber.
→ Boron Oxide (B_2O_3) is added to decrease refractive index for making cladding of optical fiber.

2. Glass - Plastic Fiber

→ Making glass core and plastic cladding.
→ Comparatively higher losses
→ The cost is reduced.

3. Plastic - Plastic Fiber

→ Both core and cladding is made of plastic
→ Very high attenuation.
→ Low cost, tough, durable and inexpensive.

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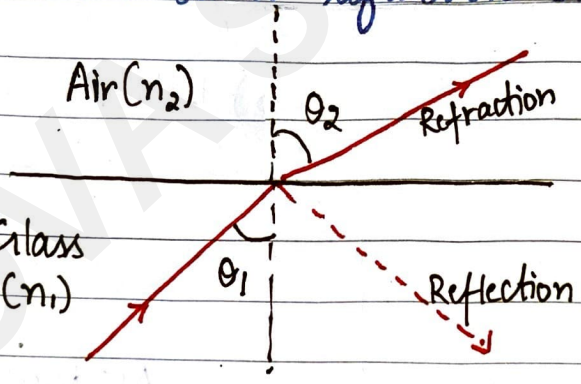
Refractive Index

The index of refraction of a material is the ratio of speed of light in a vacuum to the speed of light in the material.

$$n = \frac{c}{v}$$ where n is refractive index.

Snell's Law

When a ray of light is incident on the interface between two dielectrics of different refractive indices, reflection and refraction occur.



By Snell's law,

$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

→ When $\theta_2 = 90°$, i.e, angle of refraction is 90°

We get $\sin\theta_1 = \frac{n_2}{n_1}$

The critical angle is the angle of incidence where the angle of refraction is 90°.

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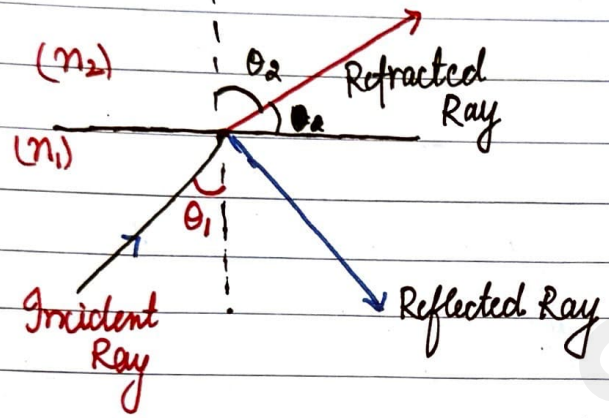
Thus we have,

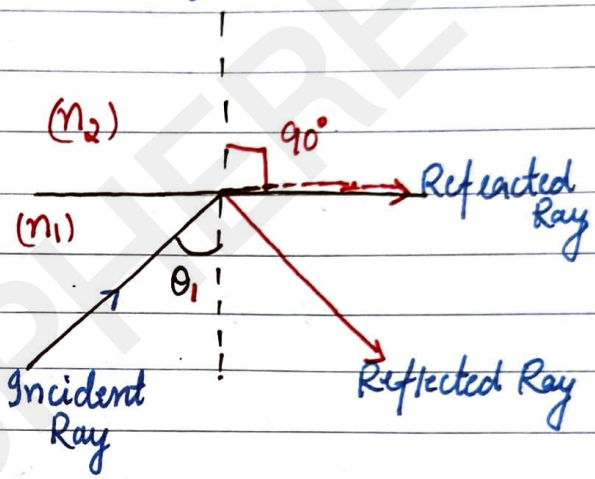
$$\theta_c = \sin^{-1}\left(\frac{n_2}{n_1}\right)$$

where θ_c is critical angle.

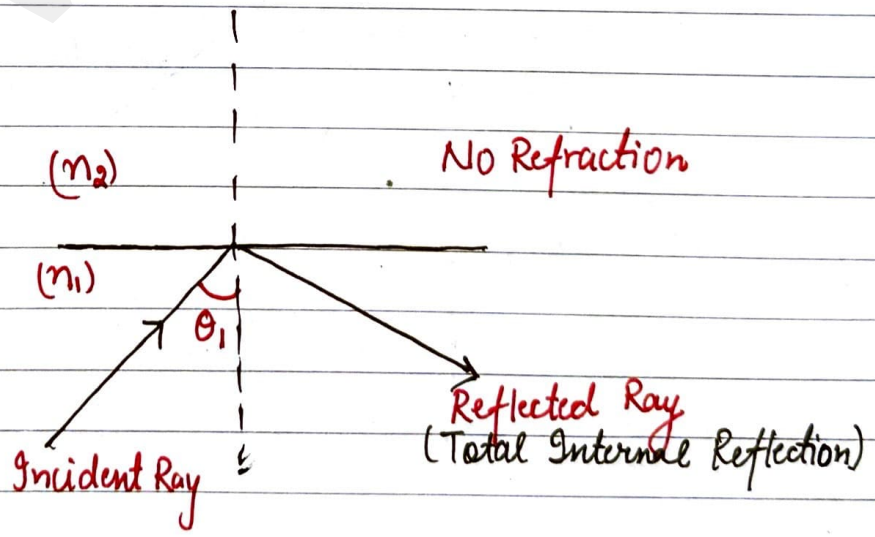
Here $n_1 > n_2$



(a) When $\theta_1 < \theta_c$
(θ_1 is incidence angle)



(b) When $\theta_1 = \theta_c$



(c) $\theta_1 > \theta_c$

At angles of incidence, $\theta_1 > \theta_c$, the light is totally reflected back into the incidence higher refractive index medium. This is known as total

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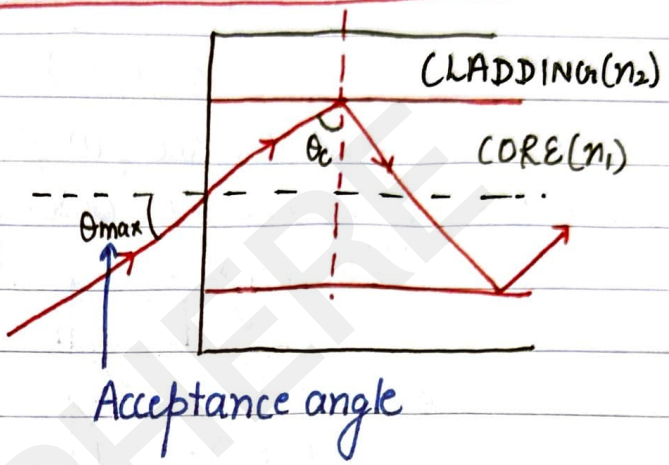
internal reflection. (TIR)

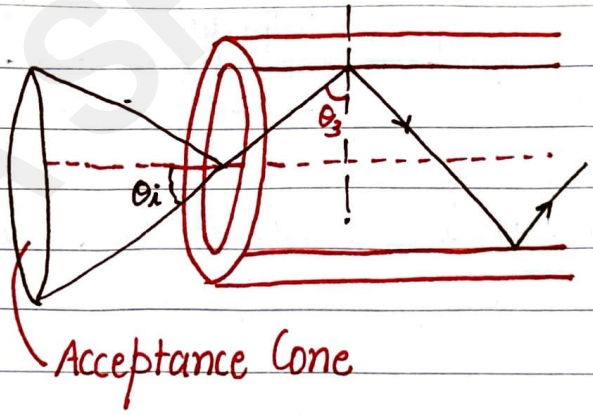
ACCEPTANCE ANGLE AND ACCEPTANCE CONE

Acceptance angle is the maximum angle of a ray hitting the fiber core which allows the incident light to be guided by the core.



Acceptance Cone

In fiber optics, the cone within which optical power may be coupled into the bound modes of an optical fiber.



→ It is set of all light rays that can enter an optical fiber and still be guided through it by total internal reflection.

→ This cone is obtained by rotating the acceptance angle about the fiber axis.

Expression of Acceptance Angle.

Since acceptance angle is the maximum angle at which when light is incident, it will be

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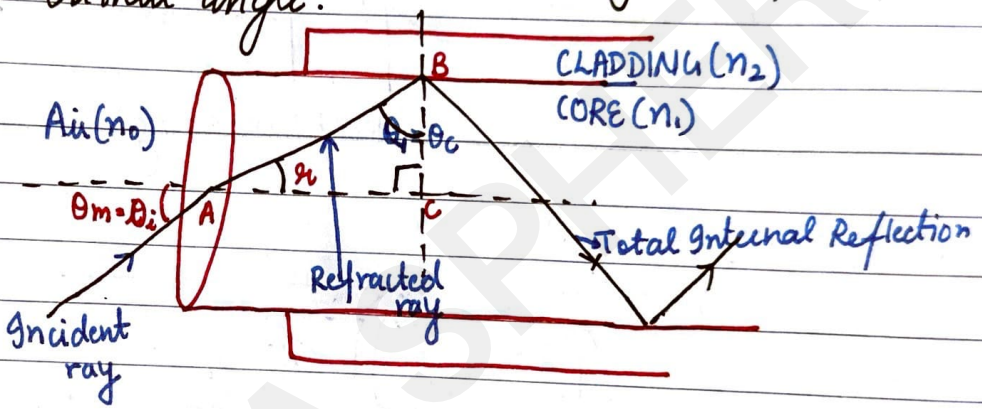
guided through the fiber, so when

$$\theta_i = \theta_m \text{ (angle of acceptance)}$$
$$\Rightarrow \theta_1 = \theta_c$$
(see figure)

Here θ_i is the incidence angle outside the fiber, θ_1 is the incidence angle at core-cladding interface and θ_c is the critical angle.



Let refractive index of Air be n_0, core be n_1 and cladding be n_2.

In figure, when $\theta_i = \theta_m$. ← (1)

$\Rightarrow$ $\angle ABC$, i.e, $\theta_1 = \theta_c$ ← (2)

Applying snell's law for air-core media -

$$n_0 \sin\theta_i = n_1 \sin r \quad \left[r = \angle BAC\right]$$
← (3)

In $\triangle ABC$, $r + \theta_1 = 90^\circ$

$\Rightarrow$ $r = 90^\circ - \theta_1$

Substituting value of r in (3) →

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$$n_0 \sin\theta_i = n_1 \sin(90^\circ - \theta_1)$$
$$n_0 \sin\theta_i = n_1 \cos\theta_1$$
$$\sin\theta_i = \frac{n_1}{n_0}\cos\theta_1$$

Substituting $\theta_i = \theta_m$ and $\theta_1 = \theta_c$ from (1) and (2)

$$\Rightarrow \sin\theta_m = \frac{n_1}{n_0}\cos\theta_c \leftarrow (4)$$

Applying snell's law at core-cladding interface →

$$n_1 \sin\theta_1 = n_2 \sin r_1$$

where r_1 is angle of refraction in cladding.

But when $\theta_1 = \theta_c$, $r_1 = 90^\circ$

$$\Rightarrow n_1 \sin\theta_c = n_2$$

$$\Rightarrow \sin\theta_c = \frac{n_2}{n_1} \leftarrow (5)$$

Also, $\sin^2\theta_c + \cos^2\theta_c = 1$

$$\Rightarrow \cos\theta_c = \sqrt{1 - \sin^2\theta_c}$$

Substituting $\sin\theta_c = \frac{n_2}{n_1}$ from (5)

$$\Rightarrow \cos\theta_c = \sqrt{1 - \frac{n_2^2}{n_1^2}} \leftarrow (6)$$

Substituting (6) in (4) →

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$$\sin\theta_m = \frac{n_1}{n_0}\sqrt{1-\frac{n_2^2}{n_1^2}}$$

$$\Rightarrow \sin\theta_m = \frac{1}{n_0}\sqrt{n_1^2-n_2^2} \quad \left[\text{Refractive index of air}(n_0) = 1\right]$$

$$\Rightarrow \boxed{\theta_m = \sin^{-1}\sqrt{n_1^2-n_2^2}}$$

NUMERICAL APERTURE

It is defined as light gathering ability of fibers optics. Mathematically given by -

$$\boxed{NA = \sin\theta_m}$$

$$\boxed{NA = \frac{\sqrt{n_1^2-n_2^2}}{n_0}}$$

Fractional Index Change

It is a mathematical quantity given as -

$$\boxed{\Delta = \frac{n_1-n_2}{n_1}}$$

where n_1 = refractive index of core
n_2 = refractive index of cladding

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Relationship between Numerical Aperture and Fractional Index Change

We know that $\Delta = \frac{n_1 - n_2}{n_1}$

$\Rightarrow \Delta . n_1 = n_1 - n_2 \leftarrow (1)$

Also, $NA = \sqrt{n_1^2 - n_2^2}$

$\Rightarrow NA = \sqrt{(n_1 + n_2)(n_1 - n_2)}$

Substituting value of $n_1 - n_2$ from (1)

$\Rightarrow NA = \sqrt{(n_1 + n_2)(\Delta . n_1)}$

Since n_1 and n_2 are very close to each other, $n_1 \approx n_2 \Rightarrow n_1 + n_2 \simeq 2n_1$

$\Rightarrow NA = \sqrt{2n_1 . n_1 . \Delta}$

$\Rightarrow \boxed{NA = n_1 \sqrt{2.\Delta}}$

V - NUMBER OR NORMALIZED FREQUENCY

V- number is a dimensionless quantity used to determine the number of modes that can propagate within the fiber. It is given by -

$$\boxed{V = \frac{2\pi a}{\lambda} (N.A)}$$

Where, a is core radius, N.A is numerical aperture
λ is incident light wavelength

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$$V = \frac{2\pi a}{\lambda} \sqrt{n_1^2 - n_2^2}$$

$$V = \frac{2\pi a}{\lambda} \cdot n_1 \sqrt{2.\Delta}$$

where Δ is fractional index change.

→ Number of modes for step-index fiber

$$N_m = \frac{V^2}{2}$$

→ Number of modes for graded-index fiber

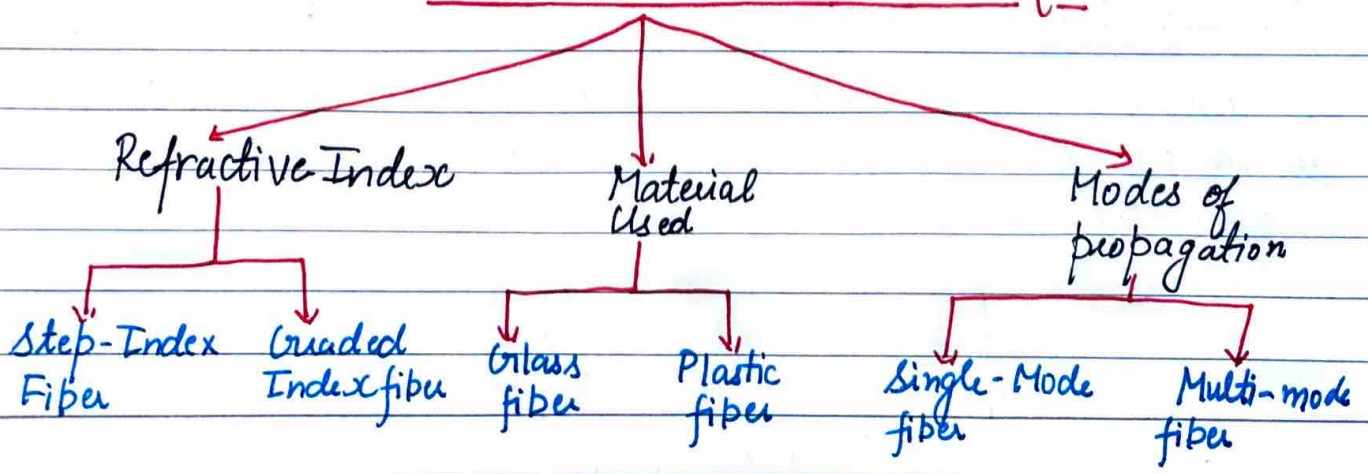
$$N_m = \frac{V^2}{4}$$

→ If $V < 2.405$, it is a single-mode fiber

→ If $V > 2.405$, it is a multi-mode fiber.

→ V can be increased by increasing core-radius or the numerical aperture of fiber.

TYPES OF OPTICAL FIBERS



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Single Mode fibers:

In a fiber, if only one mode is transmitted through it, then it is said to be a single mode fiber.

→ A typical single mode fiber has very small core radius. [diameter 8-10 μm]

→ Almost no pulse spreading, leading to clear signal transmission.

→ Supports very high bandwidth

→ It is used for long-distance communication with minimal signal loss.

→ It requires precise manufacturing and alignment, making it expensive.

Disadvantages of single mode:

→ It is hard to couple light into and out of the very small core.

→ Requires a highly directive source for proper light injection.

→ Overall system setup is more expensive.

Multimode fibers:

It is an optical fiber in which multiple light rays propagate simultaneously through the core by different paths.

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Advantages of Multi-mode fiber

1. Easy light coupling : Large core makes it easy to launch light into the fiber.
2. Low cost : Cheaper source and components can be used.
3. Simple fabrication : Manufacturing and handling are easier.
4. Less alignment precision required : Eases splicing and connections
5. Suitable for short distances : Ideal for LANs and indoor communication.

Disadvantages of Multi-mode fiber

1. There is high modal dispersion leading to pulse broadening.
2. Due to lower bandwidth, data transmission rate is limited.
3. Signal is distorted due to multiple light paths.
4. There is higher attenuation resulting in signal loss.

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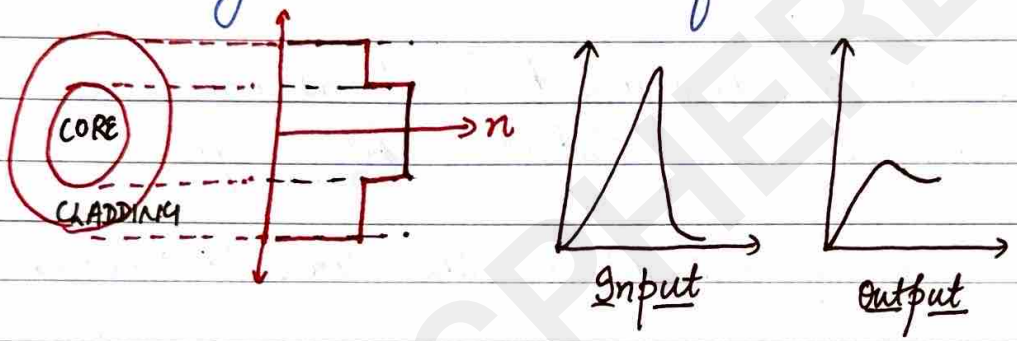
Step-Index Fiber

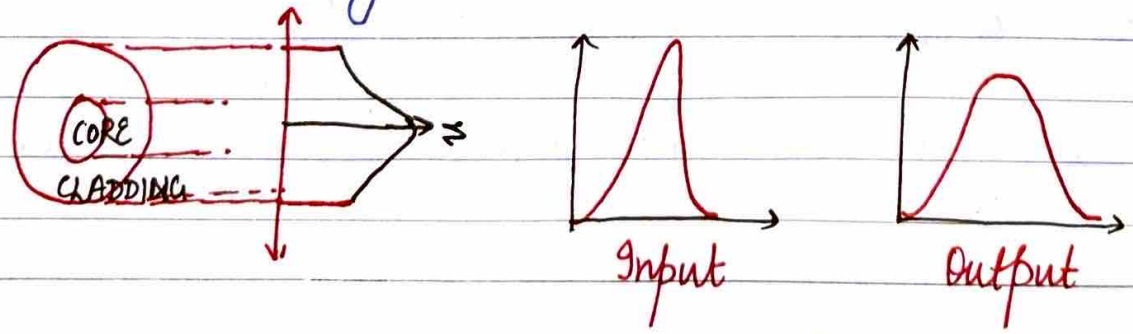
In step-index fiber, the refractive index changes in a step manner, from center of core to the outer cladding.

The step-index fiber propagates both single and multi-mode signals within the fiber core.



Graded-Index Fiber

Graded index fiber is a type of multi-mode optical fiber in which the refractive index of the core decreases gradually from the center to the cladding. The refractive index is maximum at center and decreases gradually as we move towards cladding.



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Advantages of Optical fiber communication

→ Optical fiber communication provides very high bandwidth, which allows transmission of large amounts of data at very high speeds over long distances.

→ It has very low attenuation, so the signal can travel long distances with minimal loss.

→ Optical fibers are immune to electromagnetic interference, ensuring noise-free and distortion-free signal transmission.

→ The fibers are very small in size and lightweight.

→ It offers high security since the signals are difficult to tap, reducing the chances of data leakage.

Disadvantages of optical fiber

→ The initial cost of installation is high due to expensive equipment and setup requirements.

→ Optical fibers are fragile in nature and can break easily if not handled properly.

→ Optical fibers cannot carry electrical power.

→ A specialist is needed for handling and installation of fibers.

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Applications of optical fibers

① They are widely used in communication systems for transmitting data, voice and internet signals over long distances.

② They are used in medical field, especially in endoscopy, to observe internal organs.

③ They are used in sensing applications to measure physical parameters such as temperature, pressure and strain.

④ They are used in military and defense for secure communication.

⑤ They are used in cable television and networking to deliver high quality video signals and broadband internet.

⑥ They are used in industrial inspection to examine hard to reach or hazardous areas.

Dispersion and its types

Dispersion in optical fiber is the phenomenon in which a light pulse spreads out in time as it propagates along the fiber due to different components of light travelling at different speeds.

As a result of dispersion, pulse broadening occurs, which may lead to overlapping of adjacent pulses

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and causes signal distortion in communication systems.

Types of dispersion

1. Intermodal or Modal dispersion

→ Modal dispersion occurs in multi-mode fibers where multiple modes of light propagates simultaneously. Since each mode travels along a different path, the distance covered by each ray is different.

→ Some rays travel straight through axis of fibre, while others undergo multiple reflection and follow zig-zag paths.

→ Due to these different path lengths, the time taken by each mode to reach the output end varies.

→ This results in spreading of pulse, known as intermodal dispersion.

2. Intramodal dispersion or chromatic dispersion

This dispersion occurs due to finite spectral width of light source. Even a single optical pulse consists of a range of wavelengths, each wavelength travels with a slightly different velocity in the fibre. This causes pulse broadening, leading to intramodal dispersion.

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Intramodal dispersion has two main components:

→ The first is material dispersion, which arises because the refractive index of the fiber material varies with wavelength, causing different wavelengths to propagate at different speeds.

→ The second is waveguide dispersion, which occurs due to the guiding structure of the fiber, where the distribution of light between the core and cladding varies with wavelength, affecting the propagation velocity.

→ The intramodal dispersion is present in both single mode and multi-mode fibers and play a significant role in limiting high speed optical communication systems.

ATTENUATION AND ITS TYPES

→ Attenuation refers to the reduction in intensity of light as it propagates through the fiber.

→ As the optical signal travels along the fiber, part of its energy is lost due to various mechanisms, resulting in a gradual decrease in signal strength with distance.

→ Expressed in dB/km

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Attenuation mainly occurs due to following:

1. Absorption loss: Absorption occurs when part of optical energy is absorbed by fiber material and converted to heat. The may be due to intrinsic properties of glass or impurities present in fiber.

2. Scattering loss: This arises from microscopic variations in material density and composition of fiber. The most important type is Rayleigh scattering, which causes light to scatter in different directions, reducing the transmitted intensity.

3. Bending loss: Bending losses occur when the fiber is curved or bent, due to which some of guided light escapes from the core.

Attenuation is given mathematically as -

$$\alpha = \frac{10}{L} \log_{10} \frac{P_{in}}{P_{out}}$$

where L is length, P_{in} is input power
P_{out} is output power
α is measured in dB/km.

Material Absorption losses

Material absorption in optical fiber occurs due to absorption of photons within the fiber material,

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resulting in the loss of optical fiber. When light propagates through the fiber, photons interact with the atoms of the material.

→ These photons can transfer their energy to the valence electrons, exciting them to higher energy levels. In this process, the photon is destroyed and energy is converted into other forms.

Material absorption is classified into two:

Intrinsic Absorption: It is caused due to fundamental properties of the fiber material itself. Even in a perfectly pure optical fiber with no impurities, intrinsic absorption occurs. It arises due to interaction of the photons with internal structure of material.

Extrinsic Absorption: It occurs due to the presence of impurities in the fiber material, which are introduced during the manufacturing process. Common impurities include metal ions such as iron, nickel and chromium. It is caused by electronic transition of these metal ions from one energy level to another energy level.

FIBER BENDING LOSS

Bending loss is classified according to bend radius of curvature as:

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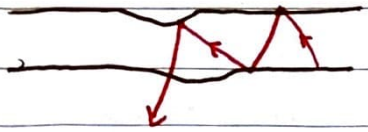
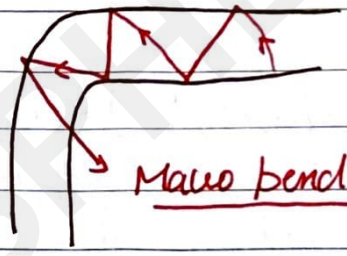
Micro bend loss : It is caused by small discontinuity or imperfection in the fiber. Uneven coating applications and improper cabling procedure increases micro bend loss.

Macro bend loss : It is observed when a fiber's bend radius of curvature is large compared to fiber diameter. These bends lead to loss of the signal.



Micro loss



Macro bend loss

Linear scattering loss

Linear scattering loss in optical fiber arises due to microscopic variations in the material density and composition of fiber. These irregularities cause the propagating light to be scattered in different directions, leading to a reduction in the transmitted optical power. This type of loss varies linearly with the input power.

→ The most significant form of scattering is Rayleigh scattering. It occurs due to random fluctuations in density and refractive index that are smaller than the wavelength of light. As a result, light is scattered in all directions, leading to attenuation.

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FORMULAS

1. Critical Angle, $\theta_c = \sin^{-1}\left(\frac{n_2}{n_1}\right)$

2. Acceptance Angle, $\theta_m = \sin^{-1}\left(\sqrt{n_1^2 - n_2^2}\right)$

3. Numerical Aperture, $NA = \sin\theta_m$

$$NA = \sqrt{n_1^2 - n_2^2}$$

4. V - number, $V = \frac{2\pi a}{\lambda}(NA)$

$$V = \frac{2\pi a}{\lambda}\sqrt{n_1^2 - n_2^2}$$

$$V = \frac{2\pi a}{\lambda} \cdot n_1\sqrt{2\cdot\Delta}$$

5. Fractional Index Change, $\Delta = \frac{n_1 - n_2}{n_1}$

6. No. of guided modes, $N_m = \frac{V^2}{2}$

7. No. of modes for graded index fiber, $N_m = \frac{V^2}{4}$

8. Attenuation, $\alpha = \frac{10}{L}\log_{10}\frac{P_{in}}{P_{out}}$

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